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Multicarrier (MC) CDMA systems have been developed and rapidly gained popularity as they capitalize on both MCM (multicarrier modulation)'s resilience to MUI and direct-sequence (DS) CDMA's robustness against frequency selectivity to mitigate both MUI and the inter-symbol interference (ISI) caused by time dispersive channels. However, the well-known near-far problem in a multiuser setting still places fundamental limitations on the performance of MC-CDMA communication systems, and this issue has been considered by very few papers. In this paper, the theoretical near-far resistance of the MMSE detector in the uplink MC-CDMA (with and without cyclic prefix (CP)) setting is derived. In turns out that the near-far resistance of MC-CDMA without CP has the same form as that of the DS-CDMA except that the user codes are IFFT transformed. Our formulation for the near-far resistance is applied to either blind or non-blind MMSE detectors. Computer simulations confirm theoretical findings.

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# NEAR-FAR RESISTANCE OF MULTICARRIER CDMA SYSTEMS

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## ABSTRACT

*Multicarrier (MC) CDMA systems have been developed and rapidly gained popularity as they capitalize on both MCM (multicarrier modulation)'s resilience to MUI and direct-sequence (DS) CDMA's robustness against frequency selectivity to mitigate both MUI and the inter-symbol interference (ISI) caused by time dispersive channels. However, the well-known near-far problem in a multiuser setting still places fundamental limitations on the performance of MC-CDMA communication systems, and this issue has been considered by very few papers. In this paper, the theoretical near-far resistance of the MMSE detector in the uplink MC-CDMA (with and without cyclic prefix (CP)) setting is derived. It turns out that the near-far resistance of MC-CDMA without CP has the same form as that of the DS-CDMA except that the user codes are IFFT transformed. Our formulation for the near-far resistance is applied to either blind or non-blind MMSE detectors. Computer simulations confirm theoretical findings.*

## 1. INTRODUCTION

New multimedia applications in the field of mobile communications require high data rate transmission under the frequency selective fading environment. The current DS-CDMA systems may become impractical when the data rate reaches very high speeds. The very short chip duration leads to severe interchip interference (ICI) due to multipath fading channels and difficulties of synchronization. The MC-CDMA technique does not suffer from such shortcomings. As a hybrid of multicarrier modulation (MCM) and DS-CDMA, each chip of the desired user's signature sequence is made longer and is modulated onto a separate subcarrier, which has narrow bandwidth undergoing frequency-flat fading. Because synchronization is very important for performance of MCM approaches, most researchers in MC-CDMA area choose to focus on the synchronous transmission scenario, i.e., downlink case. However, the well-known near-far problem in a multiuser setting (in uplink) still places fundamental limitations on the performance of MC-CDMA communication systems, and this issue has been considered by very few papers. In this paper, the theoretical near-far resistance of the MMSE detector in the uplink MC-CDMA setting with or without cyclic prefix (CP) is derived. It turns out that the near-far resistance of MC-CDMA without CP has the same form as that of the DS-CDMA except that the user codes are IFFT transformed. Our formulation for the near-far resistance is applied to either blind or non-blind MMSE detectors.

The notation used in paper follows usual convention: Vectors are denoted by symbols in boldface, $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$ are complex conjugate, transpose and conjugate transpose of $(\cdot)$, respectively.

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## 2. SYSTEM MODEL

Consider an asynchronous MC-CDMA system with $N$ subcarriers and $J$ active users in a multipath fading channel. Random binary ($\pm 1$) codes of length $N$ are used as spreading codes to distinguish different users. We will be concerned with digital wireless transmissions through linear time invariant (LTI) discrete-time baseband equivalent channels. The baseband MC-CDMA system model for the $jth$ user is presented in Figure 1 on the next page. With received baseband signal sampled at chip rate $1/T_c$ where $T_c$ is the chip duration, the discrete-time received sequence is given by

$$\bar{r}_j(n) = \sum_{l=0}^{L} h_j(l)\bar{u}_j(n-l) + v_j(n) \tag{1}$$

where $\bar{r}_j(n)$, $\bar{u}_j(n)$, $h_j(n)$ and $v_j(n)$ are $jth$ user's received signal, transmitted OFDM symbols, chip sampled multipath channel and additive white Gaussian noise, respectively. In the following, we will only consider such discrete-time equivalent models which will be assumed to satisfy the following.

*Assumption* 1*:* All user channels are FIR of order $\leq L = \bar{L} + D$, where $\bar{L}$ is the maximum delay spread of the chip

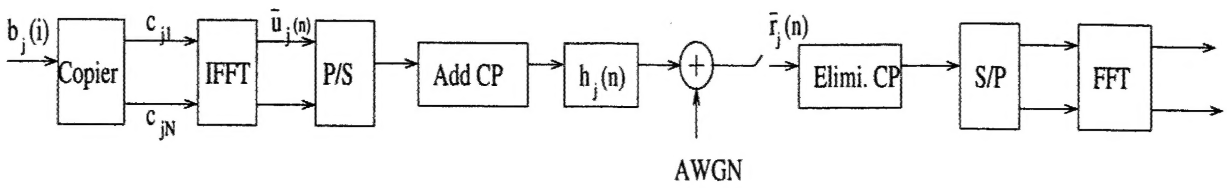


**Fig. 1.** Baseband MC-CDMA system model for the $jth$ user

sampled multipath channels and $D$ is the maximum relative asynchronous delay among the users.

The MC-CDMA model with CP was first developed by combining the OFDM and CDMA techniques [1][2]. However, due to the CP overhead, researchers are more interested in detectors for the MC-CDMA models without CP [4][5]. We will first derive the discrete-time MC-CDMA model without CP. Group the serial $\bar{u}_j(n)$ into blocks of $N$ ($N >> L$) (with CP the block size is $N+L$). Define the $jth$ user's $ith$ transmitted block to be $\bar{\mathbf{u}}_j(i) = [\bar{u}_j(iN), \bar{u}_j(iN+1), \cdots, \bar{u}_j(iN+N-1)]^T$ and $\bar{\mathbf{r}}_j(i) = [\bar{r}_j(iN), \bar{r}_j(iN+1), \cdots, \bar{r}_j(iN+N-1)]^T$ as the $ith$ received block. Using (1), we obtain

$$\bar{\mathbf{r}}_j(i) = \bar{\mathbf{H}}_{j0}\,\bar{\mathbf{u}}_j(i) + \bar{\mathbf{H}}_{j1}\,\bar{\mathbf{u}}_j(i-1) + \bar{\mathbf{v}}_j(i) \qquad (2)$$

where $\bar{\mathbf{v}}_j(i)$ is the corresponding $jth$ user's noise vector, and

$$\bar{\mathbf{H}}_{j0}' = \begin{bmatrix} h_j(0) & 0 & & \cdots & 0 \\ \vdots & h_j(0) & & & \\ h_j(L) & & \ddots & & \vdots \\ \vdots & \ddots & & \ddots & 0 \\ 0 & \cdots & h_j(L) & \cdots & h_j(0) \end{bmatrix}$$

$$\bar{\mathbf{H}}_{j1} = \begin{bmatrix} 0 & \cdots & h_j(L) & \cdots & h_j(1) \\ & & & \ddots & \vdots \\ \vdots & & & & h_j(L) \\ & & & & \vdots \\ 0 & & \cdots & & 0 \end{bmatrix}$$

Note that depending on the values of $N$ and $L$, there may be more inter-block interference (IBI) terms and correspondingly more $\bar{\mathbf{H}}_{jl_j}, l_j > 1$. In the MC-CDMA system, $\bar{\mathbf{u}}_j(i) = \mathbf{W}^H [c_{j1}, \cdots, c_{jN}]^T b_j(i) = \mathbf{W}^H \mathbf{c}_j b_j(i) = \mathbf{c}'_j\, b_j(i)$ where $\mathbf{W}^H$ is the $N \times N$ dimensional IDFT matrix with its $(m,n)th$ element as $\frac{1}{\sqrt{N}}\, e^{-j2\pi(m-1)(n-1)/N}$, $\mathbf{c}_j$ and $b_j(i)$ are the spreading code vector and $ith$ transmitted bit of the $jth$ user, respectively. $\mathbf{c}'_j = \mathbf{W}^H\, \mathbf{c}_j$ is the IDFT transformed code vector. Define the $(N+L) \times (L+1)$ matrix $\mathbf{C}'_j$ with shifted column vector $\mathbf{c}'_j$ and $jth$ user's channel vector $\mathbf{h}_j$ as

$$\mathbf{C}'_j = \begin{bmatrix} c'_{j1} & & \\ \vdots & \ddots & \\ \vdots & & c'_{j1} \\ c'_{jN} & & \vdots \\ & \ddots & \vdots \\ & & c'_{jN} \end{bmatrix}, \mathbf{h}_j = \begin{bmatrix} h_j(0) \\ \vdots \\ h_j(L) \end{bmatrix}$$

After carefully examining the structure of $\bar{\mathbf{H}}_{jl_j}$ and $\bar{\mathbf{u}}_j(i)$, we have

$$\begin{aligned} \bar{\mathbf{H}}_{jl_j}\,\bar{\mathbf{u}}_j(i) &= \mathbf{C}'_j(l_jN+1 : l_jN+N, :)\,\mathbf{h}_j\, b_j(i) \\ &\triangleq \mathbf{C}'_j(l_j)\,\mathbf{h}_j\, b_j(i) \triangleq \mathbf{H}_j(l_j)\, b_j(i) \end{aligned} \qquad (3)$$

where in the above equation, we use MATLAB representation to denote $\mathbf{C}'_j(l_j)$ as the submatrix of $\mathbf{C}'_j$ from row $l_jN+1$ to $l_jN+N$. In the receiver, the received signal is first feed through an FFT block. The total received signal at the receiver is the superposition of the data signals of the $J$ users, given by

$$\mathbf{r}(i) = \sum_{j=1}^{J} \mathbf{W}\,\bar{\mathbf{r}}_j(i) \qquad (4)$$

where $\mathbf{W}$ is the FFT matrix. Since the receiver does not know the starting time of each desired user symbol, then similar to a chip level detector [6] for an asynchronous DS-CDMA system, a smoothing factor $M$ is needed to capture a complete desired user symbol. Let $L_h = \max_{j=1}^{J} l_j + 1$ and from (2)-(4), we obtain

$$\chi_M(n) = \mathcal{H}\mathbf{b}(n) + \mathbf{v}(n) \qquad (5)$$

where $\chi_M(n) = \begin{bmatrix} \mathbf{r}^T(n) & \cdots & \mathbf{r}^T(n+M-1) \end{bmatrix}^T$, $\mathbf{b}(n) = \begin{bmatrix} \bar{\mathbf{b}}^T(n-L_h+1) & \cdots & \bar{\mathbf{b}}^T(n+M-1) \end{bmatrix}^T$, $\bar{\mathbf{b}}(n) = \begin{bmatrix} b_1(n) & \cdots & b_J(n) \end{bmatrix}^T$, $\mathbf{v}(n) = [\bar{\mathbf{v}}^T(n), \cdots, \bar{\mathbf{v}}^T(n+M-1)]^T$,

$$\mathcal{H} = \begin{bmatrix} \mathbf{WH}(L_h-1) & \cdots & \mathbf{WH}(0) & \cdots & 0 \\ \vdots & \ddots & & \ddots & \vdots \\ 0 & \cdots & \mathbf{WH}(L_h-1) & \cdots & \mathbf{WH}(0) \end{bmatrix},$$

and $\mathbf{H}(l) = [\mathbf{H}_1(l), \cdots, \mathbf{H}_J(l)]^T$. It is not hard to find that (5) has the similar form as that of the DS-CDMA [6]. Since the received signal amplitude is the combination of channel attenuation and the transmitted signal amplitude $\mathbf{b}(n)$, we can combine these two effects into one diagonal amplitude matrix $\mathbf{A}$. Thus (5) can be rewritten as

$$\chi_M(n) = \mathcal{H}\mathbf{A}\mathbf{b}(n) + \mathbf{v}(n) \tag{6}$$

with $\mathbf{b}(n)$ having unit norm, and the columns of the channel matrix $\mathcal{H}$ being all normalized.

For the MC-CDMA with CP, after the FFT and the elimination of the CP, (4) can be rewritten as, in the absence of noise,

$$\begin{aligned} \tilde{\mathbf{r}}_j(i) &= \mathbf{W}\,\mathbf{R}_{cp}\,\bar{\mathbf{H}}_{j0}\,\mathbf{T}_{cp}\,\mathbf{W}^H\,\mathbf{c}_j\,b_j(i) \\ &+ \mathbf{W}\,\mathbf{R}_{cp}\,\bar{\mathbf{H}}_{j1}\,\mathbf{T}_{cp}\,\mathbf{W}^H\,\mathbf{c}_j\,b_j(i) \end{aligned}$$

where $\mathbf{T}_{cp}$ and $\mathbf{R}_{cp}$ represent the processes of adding and elimination the CP [1]. Due to the effect of $\mathbf{T}_{cp}$ and $\mathbf{R}_{cp}$, $\mathbf{R}_{cp}\,\bar{\mathbf{H}}_{j1}\,\mathbf{T}_{cp} = 0$, the IBI term is thus eliminated. Furthermore, $\mathbf{R}_{cp}\,\bar{\mathbf{H}}_{j0}\,\mathbf{T}_{cp} \triangleq \tilde{\mathbf{H}}_{j0}$ becomes a circulant matrix with first column as $\left[\mathbf{h}_j^T, 0\cdots, 0\right]^T$.

*Fact* 1 *(Diagonalization of a circulant matrix) [1]:* An $N \times N$ circulant matrix $\tilde{\mathbf{H}}_{j0}$ can be diagonalized by pre- and post-multiplication with N-point FFT and IFFT matrices. Its diagonal elements are the corresponding FFT transform of the first column of the circulant matrix.

Therefore, the resulting channel matrix $\mathcal{H}$ for MC-CDMA with CP is reduced to $\tilde{\mathcal{H}}$

$$\tilde{\mathcal{H}} = \begin{bmatrix} c_{11}\,F_1(1) & \cdots & c_{J1}\,F_J(1) \\ \vdots & & \vdots \\ c_{1N}\,F_1(N) & \cdots & c_{JN}\,F_J(N) \end{bmatrix} \tag{7}$$

where $[F_j(1), \cdots, F_j(N)]^T = \mathbf{W}\left[\mathbf{h}_j^T, 0\cdots, 0\right]^T$.

The following assumptions will be made throughout this paper.

1. The symbols $b_j(n)$ are uncorrelated in time; $b_i(n)$ and $b_j(n)$, $i \neq j$ are uncorrelated.
2. The channel matrices $\mathcal{H}$ in (6) and $\tilde{\mathcal{H}}$ in (7) are of full column rank (known as the identifiability condition in the blind multiuser detection/equalization literature [6][7]).

### 3. NEAR-FAR RESISTANCE OF MC-CDMA

In this section, first we prove that $\mathbf{f}_{mmse} = A_d\mathbf{R}^+\mathbf{H}_d$ is the general MMSE detector for the signal model (6), where "+" represents pseudoinverse, $\mathbf{R}$ is the autocorrelation matrix of the received signal vector $\chi_M(n)$, $\mathbf{H}_d$ is one of the columns in $\mathcal{H}$ corresponding to the desired user's symbol we want to detect, and $A_d$ is the received signal amplitude of the desired user. According to [10], the MMSE detector can be obtained by the Wiener-Hopf equation

$$\begin{aligned} \mathbf{f}_{mmse} &= \mathbf{R}^{-1}E\left\{\chi_M\, b_d^*(n)\right\} \\ &= \mathbf{R}^{-1}\,\mathcal{H}\mathbf{A}\,[0, \cdots, 0, 1, 0, \cdots, 0]^T \\ &= A_d\,\mathbf{R}^{-1}\,\mathbf{H}_d \end{aligned} \tag{8}$$

where $b_d(n)$ is the desired user's transmitted symbol, and 1 is in the *dth* position. Since the zero forcing (ZF) detector will be used in the derivation of the near-far resistance, we first show that when noise approaches to zero, these two detectors are proportional to each other. Assume there is no noise and the zero forcing detector is $\mathbf{f}_{zf}$. Applying $\mathbf{f}_{zf}^H$ to (6), we require

$$\begin{aligned} \mathbf{f}_{zf}^H\chi_M(n) &= \mathbf{f}_{zf}^H\mathcal{H}\mathbf{A}\mathbf{b}(n) = [0\cdots 0\,\alpha\, 0\cdots 0]\,\mathbf{A}\mathbf{b}(n) \\ &= \alpha A_d b_d(n) \end{aligned} \tag{9}$$

where $\alpha = \mathbf{f}_{zf}^H\mathbf{H}_d$ is a constant and at the *dth* position. Then right multiply (9) by $\chi_M^H(n)$ and take expectation, we obtain $\mathbf{f}_{zf}^H E\left[\chi_M(n)\,\chi_M^H(n)\right] = \alpha A_d^2\mathbf{H}_d^H$. Therefore, the zero forcing detector has the expression $\mathbf{f}_{zf} = \alpha A_d^2\mathbf{R}^{-1}\mathbf{H}_d$. It is straightforward to show that for the noiseless case the ZF and MMSE detectors are related by $\mathbf{f}_{zf} = \alpha\, A_d\, \mathbf{f}_{mmse}$.

By applying the zero forcing detector to the received signal vector $\chi_M(n)$, the output contains only the useful signal and ambient Gaussian noise. The energy of the useful signal at the output is $E_s = A_d^2\mathbf{f}_{zf}^H\mathbf{H}_d\mathbf{H}_d^H\mathbf{f}_{zf}$, the variance of the noise is $E_n = \sigma^2\,\mathbf{f}_{zf}^H\mathbf{f}_{zf}$ where $\sigma^2$ is the power spectral density of white Gaussian noise. Using the definition in [8], the asymptotic multiuser efficiency (AME) for the desired user is

$$\begin{aligned} \bar{\eta}_d &= \lim_{\sigma\to 0}\frac{e_j(\sigma)}{A_d^2} = \lim_{\sigma\to 0}\frac{\sigma^2\left[Q^{-1}(P_d(\sigma))\right]^2}{A_d^2} \\ &= \lim_{\sigma\to 0}\frac{\sigma^2\, E_s/E_n}{A_d^2} = \lim_{\sigma\to 0}\frac{\sigma^2\,A_d^2\,\mathbf{f}_{zf}^H\,\mathbf{H}_d\,\mathbf{H}_d^H\,\mathbf{f}_{zf}}{\sigma^2\,\mathbf{f}_{zf}^H\,\mathbf{f}_{zf}\,A_d^2} \\ &= \lim_{\sigma\to 0}\frac{\mathbf{f}_{mmse}^H\,\mathbf{H}_d\,\mathbf{H}_d^H\,\mathbf{f}_{mmse}}{\mathbf{f}_{mmse}^H\,\mathbf{f}_{mmse}} \\ &= \lim_{\sigma\to 0}\frac{\mathbf{H}_d^H\left(\mathcal{H}\mathbf{A}\,\mathcal{H}^H+\sigma^2\,\mathbf{I}\right)^+\mathbf{H}_d\,\mathbf{H}_d^H\left(\mathcal{H}\mathbf{A}\,\mathcal{H}^H+\sigma^2\,\mathbf{I}\right)^+\mathbf{H}_d}{\mathbf{H}_d^H\,(\mathcal{H}\mathbf{A}\,\mathcal{H}^H+\sigma^2\,\mathbf{I})^+\,(\mathcal{H}\mathbf{A}\,\mathcal{H}^H+\sigma^2\,\mathbf{I})^+\,\mathbf{H}_d} \\ &= \frac{\mathbf{H}_d^H\,\mathcal{H}^{H+}\,\mathbf{A}^{-1}\mathcal{H}^+\mathbf{H}_d\mathbf{H}_d^H\,\mathcal{H}^{H+}\,\mathbf{A}^{-1}\mathcal{H}^+\mathbf{H}_d}{\mathbf{H}_d^H\,\mathcal{H}^{H+}\,\mathbf{A}^{-1}\mathcal{H}^+\,\mathcal{H}^{H+}\,\mathbf{A}^{-1}\mathcal{H}^+\mathbf{H}_d} \\ &= \frac{A_d^{-2}}{\mathbf{H}_d^H\mathcal{H}^{+H}\mathbf{A}^{-1}\,(\mathcal{H}^H\mathcal{H})^{-1}\,\mathbf{A}^{-1}\mathcal{H}^+\mathbf{H}_d} \\ &= \frac{1}{(\mathcal{H}^H\mathcal{H})^{-1}_{(d,d)}} \end{aligned} \tag{10}$$

where $P_d(\sigma) = Q\left(\sqrt{\frac{E_s}{E_n}}\right)$, and $Q$ is the complementary Gaussian cumulative distribution function. In (10) we

have used the facts that $(\mathcal{H}\mathbf{A}\mathcal{H}^H)^+ = (\mathcal{H}^+)^H \mathbf{A}^{-1}\mathcal{H}^+$, $(\mathcal{H}^H\mathcal{H})^+ = \mathcal{H}^+ (\mathcal{H}^+)^H$ and $\mathcal{H}^+\mathbf{H}_d = [0\cdots010\cdots0]^H$, where 1 is in the $dth$ position. From (10), it is seen that the AME does not depend on the interfering signal amplitudes. Thus, it is equal to the near-far resistance $\eta_d$ [8]. It then follows that

$$\eta_d = \bar{\eta}_d = \frac{1}{(\mathcal{H}^H\mathcal{H})^{-1}_{(d,d)}} \tag{11}$$

We can see that the near-far resistance of MMSE detector of MC-CDMA without CP has the same form as that of DS-CDMA [6] [9]. The only difference is that in the MC-CDMA setting the user codes are IFFT transformed. Due to the property of IFFT matrix (i.e., if the original users' codes are orthogonal, the resulting IFFT transformed users' codes are still orthogonal), from (11), one can expect that the near-far resistance of MC-CDMA without CP should be quite similar as that of DS-CDMA systems.

Following the steps of (10), it can be shown that the near-far resistance of MMSE detector of MC-CDMA with CP has the similar form as (11) with $\mathcal{H}$ now substituted by $\bar{\mathcal{H}}$. Since the multiuser interference (MUI) is reduced through the IBI free transmission in MC-CDMA with CP, we can expect that MC-CDMA with CP is more near-far resistant than MC-CDMA without CP at the expense of low bandwidth efficiency. Finally, we should point out that (11) is the theoretical value of near-far resistance and may not be achieved in practical situations.

## 4. SIMULATIONS

Simulation examples are presented to compare the theoretical and practical near-far resistance of two blind detection method i.e., the subspace method [6] and the linear prediction method [7] under both DS-CDMA and MC-CDMA settings. The practical near-far resistance of the desired user is calculated as $\eta = \frac{\|\mathbf{f}^H \mathbf{H}_d\|^2}{\mathbf{f}^H\mathbf{f}}$ in the noise free situation. 1000 symbols are used to estimate various detectors. In all of the simulations, the users' spreading codes were randomly generated binary ($\pm1$, with equal probability) sequences, the number of subcarriers $N = 64$. The symbol length is also 64 samples. The multipath channels for each user have ten paths which may not be uniformly spaced in time. The maximum multipath delay spread of the channel is one fourth of the symbol length. The path gains are generated according to Gaussian distribution with zero means and unit variances. The maximum asynchronous user delay $D$ is one half of the symbol interval. In DS-CDMA the processing gain is chosen as 64 to retain the same bandwidth as that of the MC-CDMA. The channels for each user were randomly generated in each of the 100 Monte Carlo runs. All input symbols are drawn from a BPSK constellation and then multiplied by various magnitude factors to generate the near-far situations. All users other than the desired user have the same signal power. The near-far ratio is defined as $20\log_{10} {}^{A_i}/_{A_1}$ for $i \neq 1$, where subscript 1 denotes the desired user. The smoothing factor $M = 2$ is used for all algorithms. For the signal subspace in [6], the rank was determined by taking empirically selected thresholds .

| Near-far ratio | 0 dB | 10 dB | 20 dB |
|---|---|---|---|
| DS-T | 0.3127 | 0.3108 | 0.3073 |
| MC-T | 0.3255 | 0.3272 | 0.3089 |
| DS-P-SS | 0.2666 | 0.2780 | 0.2503 |
| MC-P-SS | 0.2693 | 0.2821 | 0.2411 |
| DS-P-LP | 0.2545 | 0.2708 | 0.2802 |
| MC-P-LP | 0.2501 | 0.2853 | 0.2886 |

**Table 1.** Comparison of theoretical and practical near-far resistance of [6][7] under different near-far ratio. DS: DS-CDMA, MC: MC-CDMA without CP, T: Theoretical value, P: Practical (simulation) value, SS: Subspace method [6], LP: Linear prediction method [7].

*Example 1: MC-CDMA without CP vs. DS-CDMA*

In this example, we use computer simulations to verify our conclusions on the near-far resistance of MC-CDMA without CP by comparing with the theoretical values (11) and with those of DS-CDMA. The simulation is set under three different near-far ratios (i.e., $0\,dB$ $10\,dB$ and $20\,dB$). The number of active users is 30. The results are presented in Table 1. From the table, it can be seen that the near-far resistance of MC-CDMA without CP is almost the same as that of DS-CDMA.

*Example 2: Near-far resistance vs. system load*

In this example, we compare the practical near-far resistance of different detectors with respect to different number of active users at $20\,dB$ near-far ratio. It can been seen from Figure 2 that the theoretical as well as the practical near-far resistance of DS-CDMA and MC-CDMA without CP is still quite similar, while MC-CDMA with CP has much better performance.[1] As mentioned before, this performance gain is achieved at the expense of reduced bandwidth efficiency. Furthermore, it can be seen that the near-far resistance decreases when the system load increases. This is because more active users lead to more MUI and thus more severe near-far problem.

*Example 3: Near-far resistance vs. symbol length*

In this example, we compare the practical near-far resistance of different detectors with respect to different length of symbol record at $20\,dB$ near-far ratio. The system has 30 active users. From the simulation results, it can be seen that when more number of symbols were used to estimate the

[1] Linear prediction method [7] is not applicable to MC-CDMA with CP

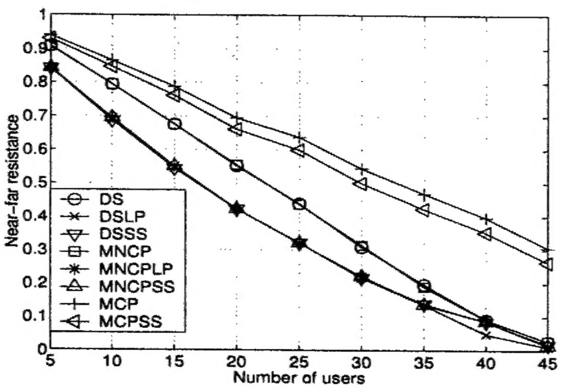


**Fig. 2.** Near-far resistance vs different number of users, $20\,dB$ near-far ratio. o: Theoretical near -far resistance of DS-CDMA (DS); $\times$: Linear prediction under DS-CDMA (DSLP); $\nabla$: Subspace under DS-CDMA (DSSS); $\square$: Theoretical near -far resistance of MC-CDMA without CP (MNCP); $*$: Linear prediction under MC-CDMA without CP; $\triangle$: Subspace under MC-CDMA without CP; $+$: Theoretical near-far resistance of MC-CDMA with CP (MCP); $\triangleleft$: Subspace under MC-CDMA with CP (MCPSS).

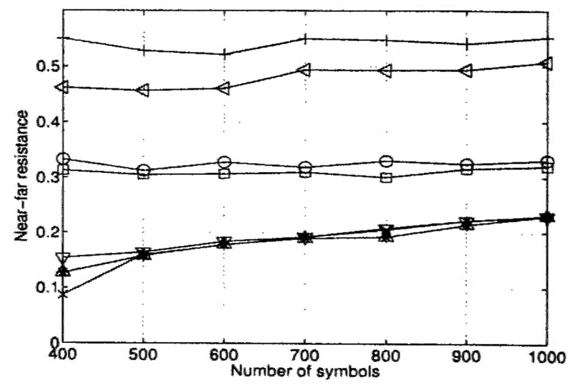


**Fig. 3.** Near-far resistance vs different number of symbols, $20\,dB$ near-far ratio, 30 active users. o: Theoretical near -far resistance of DS-CDMA (DS); $\times$: Linear prediction under DS-CDMA (DSLP); $\nabla$: Subspace under DS-CDMA (DSSS); $\square$: Theoretical near -far resistance of MC-CDMA without CP (MNCP); $*$: Linear prediction under MC-CDMA without CP; $\triangle$: Subspace under MC-CDMA without CP; $+$: Theoretical near-far resistance of MC-CDMA with CP (MCP); $\triangleleft$: Subspace under MC-CDMA with CP (MCPSS).

detector, the performance on near-far resistance becomes slightly better in all simulated algorithms since detector **f** is estimated more accurately.

## 5. CONCLUSIONS

The theoretical near-far resistance of MMSE detector in MC-CDMA system has been derived. Numerical comparison of near-far resistance between DS-CDMA and MC-CDMA is presented. It is shown that the near-far resistance of MC-CDMA without CP is very similar to that of DS-CDMA systems, while MC-CDMA with CP has much better performance on near-far resistance at the expense of reduced bandwidth efficiency.

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